High-rate plants for anaerobic treatment of wastewater and production of biogas

1. Introduction

In May 1988 in a suburb of Cali in Colombia a little high-rate pilot plant had been set into operation treating the wastewater of the small slaughterhouse of a village, the wastewater of a household of 20 persons and the washing water deluted effluents of a pig stable.

Based on the encouraging results of this high-rate plant further plants for the treatment of different kinds of substrates have been put into operation, among these one demonstration plant close to Chiang Mai in the North of Thailand.

All these plants are now between one and three years successfully under operation, enough reason to explain in this essay their basics of functioning, their field of application and to emphazise their further dissemination.

At this point the author would like to express his thanks besides the plant-owners above all the members of the different institutions, which participated in the activities, among these the GTZ (Germany), the Oekotop (Germany), the Chiang Mai University and the Department of Agricultural Extention (Thailand) and the Coporación Autónoma del Valle de Cauca (CVC) (Colombia).

Without their support this work never would have been possible.

2. The field of application of through-flow and high-rate plants

2.1 The kinetics of through-flow plants

There are several processes of producing biogas. The most extensively applied process is the through-flow plant which has been used for approx. 65 years in municipal wastewater technology and for approx. 45 years in agriculture.

The through-flow plant has a constant, totally mixed digester volume V_R and receives a constant daily input $\dot{V}_S$ (Figure 1). The central feature of plants of this type is their time-constant volume of biogas V_G or methane V_M produced daily and their constant mass of anaerobic bacteria x.

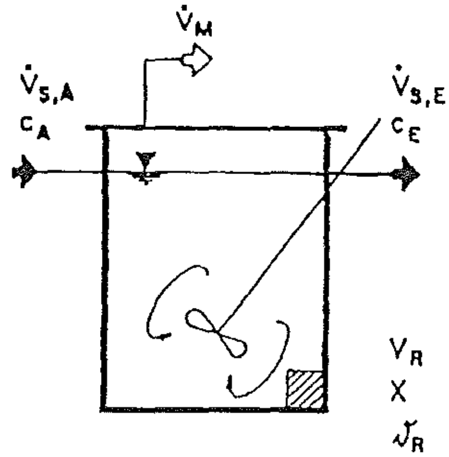


Fig. 1: Scheme of a through-flow plant

Constant values:

$\dot{V}_{Si}$:	[m³/d]	volume of daily influent
c_{Si}:	[mg/l]	concentration of pollution in the influent
$\dot{V}_{Se}$:	[m³/d]	volume of daily effluent
c_{Se}:	[mg/l]	concentration of pollution in the effluent
$\dot{V}_M$:	[m³/d]	daily methane volume (daily methane production)
V_R:	[m³]	reactor volume
x:	[kg]	mass of bacteria
ϑ_R:	[°C]	process temperature

Fig. 2 shows typical forms of construction for the through-flow plant. One is the fixed dome plant with compensation tank. Constructions of this type with a digester volume of between 5 and 35 m³ are preferred in the anaerobic treatment of animal excrements. All these plants are constructed below ground level.

When greater digester volumes are required the reactor has to be set up on the ground because the costs of excavation become more and more expensive. In this case the plant might be build as a tank with external stirring and covered by a plastic foil. In this way digester volumes of 100 - 500 m³ can be achieved. If the reactors are to become even larger the plants can no longer be economically constructed in reinforced concrete. Instead of this constructing the plant of prestressed concrete in climbing formwork would be more favourable. Digesters up to a volume of 15,000 m³ have been erected by this method.

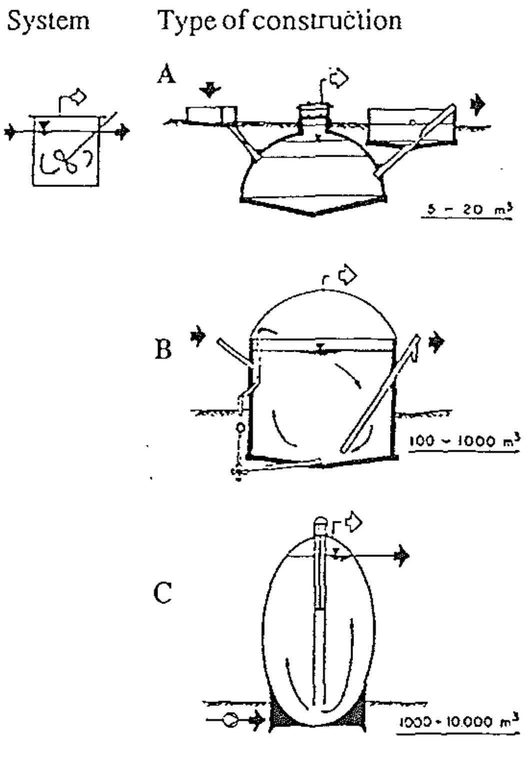


Fig.2: Typical construction types of through-flow plants

A: Fixed dome plant with compensation tank in brickwork

B: Completely mixed tank in reinforced concrete covered with a plastik foil. External stirring device.

C: Completely mixed tank in prestressed concrete. Internal stirring device

In the through-flow plant the volume of methane from an input mass of total solids $V^*_{M,TS}$ is dependent upon the retention time t_R, the type of substrate and the process temperature ϑ_R.

$$V^*_{M,TS} = f(t_R, \text{type of substrate}, \vartheta_R) \quad (1)$$

To calculate the daily output of methane V_M which can be produced by the plant $V_{M,TS}$ must be multiplied by the mass of total solids m_{ts} which is fed into the digester daily.

It is:

$$V^*_M = V_{M,TS} * \dot{m}_{ts} \quad (2)$$

Fig. 3 shows the daily methane yield $V^*_{M,TS}$ derived from the input of total solids in dependence on retention time t_R for liquid pig and cattle manure at a process temperature of 30 - 35°C. It can be observed how the methane yield V_M rises with an increase in retention time. The maximum methane yield - corresponding to maximum digestion of the organic substances - is achieved at a retention time of "infinite".

Fig. 4 illustrates the influence of temperature on the anaerobic process using liquid pig manure as an example.

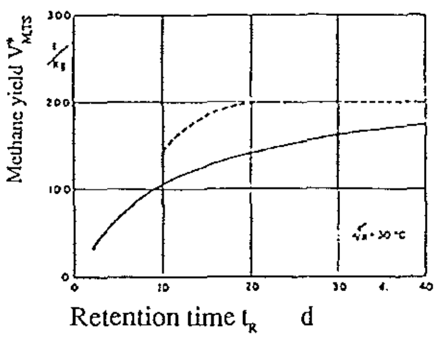


Fig.3: Methane yield $V^*_{M,TS}$ related to the total solids of the afflux versus retention time t_R and the kind of substrate (e.g. liquid pig and cattle manure).

process temperature: 30 - 35 °C.

content c_{TS} of total solids:

- - - - liquid pig manure: 6 %

——— liquid cattle manure: 10 %

With decreasing temperature it can be observed how the rate of digestion considerably decreases: At 20 °C process temperature and 40 days retention time the same methane yield is attained as at a temperature of 30°C and 20 days retention time. It can be seen further that the curves are very similar and with a compensation factor of $a\vartheta_R$ follow the same course.

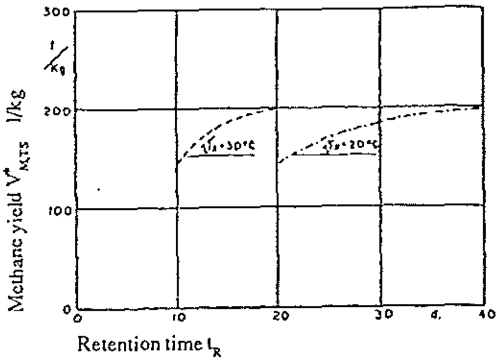


Fig.4: Methane yield $V^*_{M,TS}$ related to the total solids of the afflux versus retention time t_R and the process temperature ϑ_R.
Type of substrate: liquid pig manure with a total solids content of 6 %.

Fig. 5 demonstrates in simple terms the dependance between the compensation factor $a\vartheta_R$, the relative reaction speed and the process temperature ϑ_R. The exponential relation of the values becomes apparent. Biological processes like the anaerobic process are controlled or catalysed by enzymes. To a great extent the activity of these biocatalysts determines the reaction rate in biological digesting and biosynthesis processes. Basically, these processes take place more quickly the higher the temperature of the reaction. However, the enzymes' sensitivity of the anaerobic bacteria to temperatures over 40 - 50 °C restricts an increase in temperature. The ambient temperatures in tropical and subtropical regions is between 15 and 30 °C even up to hights of 2,000 m above sea level. This allows satisfactory to excellent reaction rates, and allows to construct the plants in a relative simple

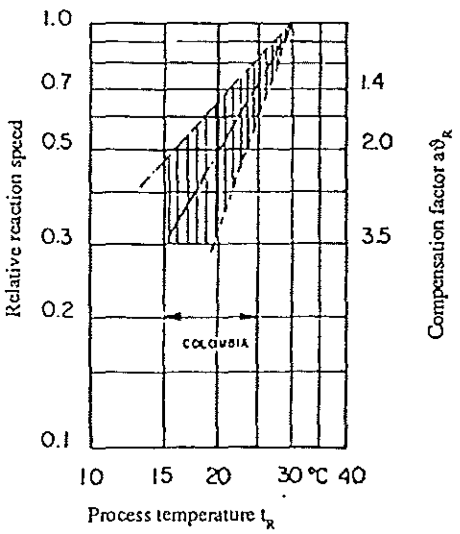


Fig.5: Relative reaction speed and compen sation factor $a\vartheta_R$ versus process temperature t_R.

and expenditure (cost) saving manner as heating systems and isolating measures for the biogas plants are not required.

The most important dimensioning parameter of biogas plants is the reactor volume V_R. For through-flow plants the reactor volume is defined by the product of daily input of substrate $\dot{V}_S$, retention time t_R and the temperature compensation factor $a\vartheta_R$.

It is:

$$V_R = \dot{V}_S * t_{R,30} * a\vartheta_R \qquad (3)$$

with $t_{R,30}$: retention time at 30°C process temperature ϑ_R.

In dimensioning plants the daily input of substrate V^*_S, the process temperature ϑ_R and thus the temperature compensation factor $a\vartheta_R$ are determined values. Only the retention time t_R is variable. Considered economically [1], the optimum retention time is shown to be at the point where the daily mass input in form of total solids is almost completely digested; i.e. at 30°C process temperature (Fig. 3) for liquid pig manure at 20 - 25 and liquid cattle manure at 30 - 35 days. According to the individual digestion quality of the substrate, the values for the retention time lie within the range of 10 to 40 days. If the retention time is less than 10 days the digestion is incomplete and the process becomes unstable. Values of less than 3 days cannot be achieved as this is below the multiplication time of the methane bacteria. This leads to the methane bacteria population being washed out of the reactor and means a complete breakdown in the biogas process.

2.2 Limits in the application of through-flow plants

The limits of practical application of the through-flow plants appear when one starts to dilute a definite pollution load m_{S_0} - measured for example as an total solids (TS) or chemical oxygen demand (COD) - with water.

If one has a defined pollution load and dilutes its concentration in the daily input volume by adding a defined volume of water this has, according to equations (1) and (2), no influence on the daily output of methane produced by the plant. On the other hand, by the increase of liquid the digester volume increases according to equation (3) - and this in equal proportion. By this way the methane produced falls in relation to the reactor volume. This has a very negative influence on the economic efficiency of this kind of process.

Table 1 shows that compared to the situation in Europe, the liquid manure derived from pig farms for example in Columbia or Thailand is diluted with washing water and thus strongly weakened by approx. factor 20. Therefore these reactors are to be designed larger by factor 20 than this would be necessary in Europe in order to achieve the same full gas production.

Table 1 shows further substrates like wastewater from coffee, cassava and meat processing industries in agriculture as well as municipal wastewater. Anaerobic processing of these wastewaters in through-flow plants is economiccally uninteresting due to the large reactor volumes derived from the high retention time of the through-flow plants and to the low methane yield per cubic metre of digester volume resulting from the low concentration of substrate.

Therefore in the case of the treatment of greatly diluted substrates the aerobic process, as opposed to the anaerobic process is always the superior alternative, especially when in addition to the aspect of energy production the aspect of wastewater treatment is also considered.

Table 1: Comparison between recommended retention times for the digestion of different kinds of substrates in through-flow and high-rate plants at ambient temperature (20 °C)

Substrate	Pollution in COD (mg/l	Retention time at 20°C Through-low plant d (days)	High-rate plant h (hours)
Pig or cow-manure with urine;	100 - 150.000	40d - 60d	-
Diluted with washing water	5 - 7.500	40d - 60d	aprox. 4d
Slaughterhouse	3 - 17.000	weeks	10 - 20h
Coffee	5 - 20.000	weeks	18h
Cassava	3 - 5.000	weeks	hours
Municipal wastewater	400 - 500	weeks	6 - 8h

2.3 The field of application of the high-rate plants

This situation has taken a decisive turn in the last ten years thanks to intensive research and development work.

In simple terms, the dimensioning of the new generation of reactors is no longer carried out according to the retention time t_R but according to the volumetric loading rate B_R.

The volumetric loading rate B_R is the quotient from the daily pollution load $\dot{S}_i$ and the reactor volume V_R. The daily pollution load $\dot{S}_i$ is the product of the pollution concentration c_{COD} and daily input volume of substrate $\dot{V}_{Si}$.

Thus it is:

$$B_R = \dot{S}_i / V_R = \dot{V}_{Si} * c_{COD} / V_R \qquad (4)$$

where c_{COD}: pollution concentration measured as the chemical oxygen demand (COD).

Thus, if the pollution load is diluted with water this will have no effect on the dimensioning since the pollution load itself does not change.

This fact means that particularly where low substrate concentrations are concerned, the retention time of several weeks can be reduced to several hours, i.e. a robic activated sludge process and the uflow anaerobic sludge bed process. The fixed bed reactor (A) is a reactor which is filled with support material. This support material can consist either of natural (bamboo sticks, stones) or artificial (plastic foil, plastic slabs or plastic foam) substances. The reactor concentrates the biomass by providing sufficient surface capacity for the biomass to settle and grow locally. Reactor B (anaerobic activated sludge process) and C (upflow anaerobic sludge bed process) retain the biomass by sedimentation.

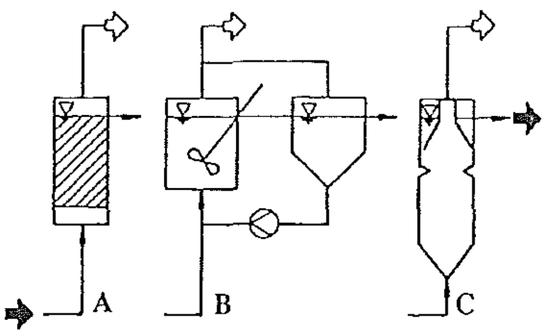


Fig.6: Scheme of three typical high-rate processes

A: anaerobic fixed bed reactor

B: anaerobic activated sludge process

C: upflow anaerobic sludge bed (UASB)

The construction and extension activities of the GTZ are restricted to the sludge bed reactor.

Organic contaminated wastewater can be subdivided into two kinds of substrates:

- substrates, where the dissolved solids form the main fraction
- substrates with a high content of coarse suspended solids

Both substrates need a different treatment concept and reactor design [2-7] as will be explained in the following chapters:

3. Designs for the treatment of substrates, where the dissolved solids form the main fraction

Fig. 7a illustrates how a reactor can look for substrates, where the dissolved solids form the main fraction. This one was designed within the activities of the GTZ/Oekotop/CVC project 'Convenio Colombo Alemán de Biogas' in Colombia on a technical scale in order to treat wastewater from a coffee processing factory [2-4]. It should also be suitable without any great structural alterations for the treatment from cassava and municipal wastewater combined with production of energy.

The volume of this digester should be sufficient to treat the municipal wastewater of 80 inhabitants.

Fig. 7b shows another digester, one of two units of 200 m^3 volume each, designed within the activities of the GTZ - Chiang Mai University - Department of Agricultural Extention - project (Thai-German Biogas Programme) in Thailand for the treatment of 6,000 population equivalents (P.E.) of municipal wastewater [6,7]. Unfortunately within the GTZ activities none of these plants could be taken into operation.

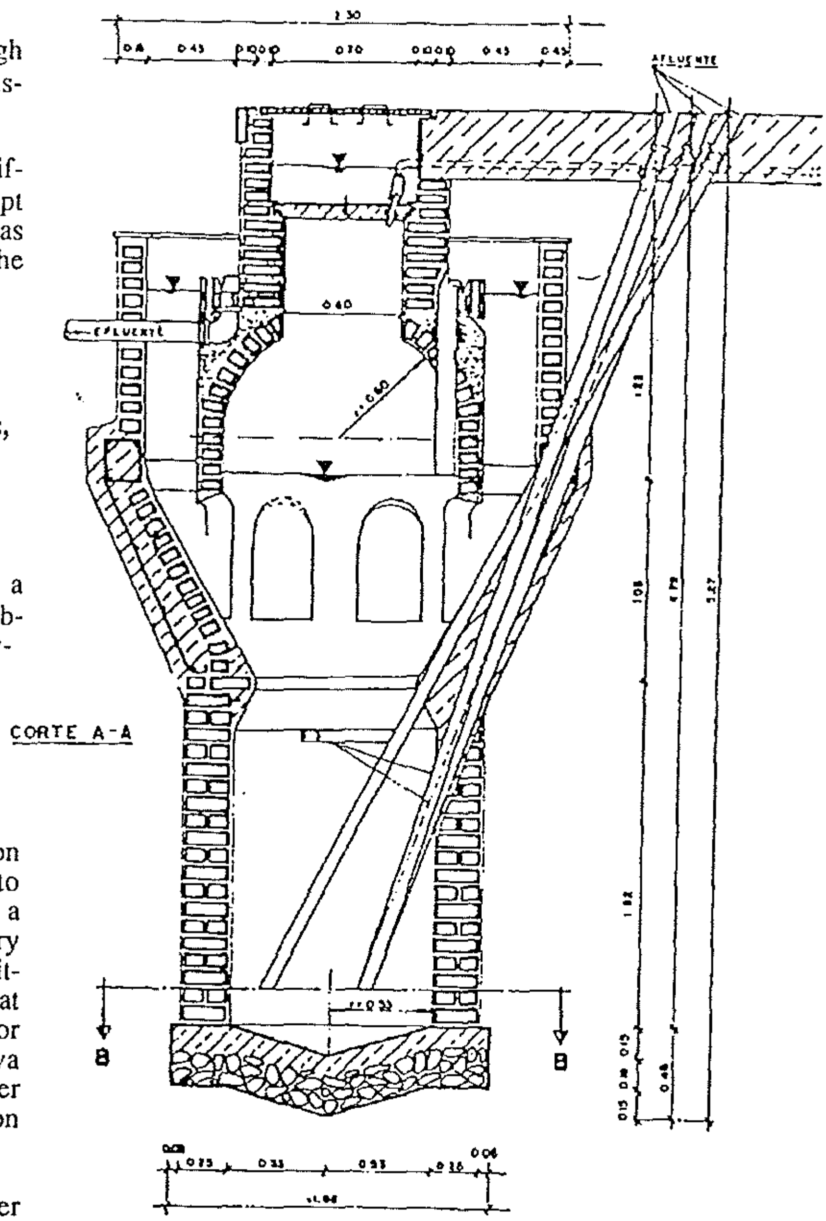


Fig. 7: Reactors in brickwork according to the upflow sludge blanket process (UASB) for anaerobic treatment of wastewater containing organic compounds which are mainly present in a dissolved form or can be easy hydrolyzed, like coffee, cassava and municipal wastewater.

Fig.7a: 4 m^3 reactor with 0,7 m^3 biogas storage under the fixed dome for the treatment of wastewater from the proces sing of coffee (60 P.E.); vertical cross section.

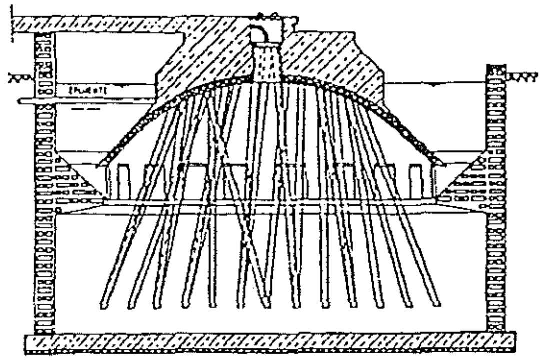


Fig. 7b: 200 m³ reactor with 23 m³ biogas storage under the fixed dome for the anaerobic treatment of 3,000 P.E. municipal wastewater; vertical cross section

4. Designs for the treatment of substrates with a high content of coarse suspended solids - Wastewater from pig fattening industry and slaughterhouses

4.1 Introduction

The wastewater from slaughterhouses and intensive pig farming is a good example for a substrate with a high content of coarse suspended solids. It is a highly contaminated water containing mainly organic compounds.

- Wastewater from intensive animal farming

The characteristics of liquid pig manure can be described by the following parameters:

- VS content: 6 - 9 %
- COD total: 100,000 - 150,000 mg/l

The volume and load of pollution can be taken from the table below:

Type of animal	mass of substrate	mass of total solids	mass of volatile solids
	kg/LU.d	kg/LU.d	kg/LU.d
pig	37	3.1	2.5

Table 2: Daily mass of substrate, total solids and volatile solids per livestock unit (LU) in pig farming (One LU correns-ponds to 500 kg live weight) [1].

The values in Table 2 vary according to feeding. They are influenced to a much greater extent by the type of stabling. According to investigations carried out in the laboratory of the Corporación Autónoma del Valle de Cauca (CVC) in Columbia an additional quantity of 400 to 800 kg of washing water per livestock unit per day can be reckoned with. Nearly the same result could be found in Thailand.

According to this the liquid pig manure is considerably diluted. The COD concentration then sinks to values around 5,000 to 7,000 mg/l.

According to VAN VELSEN [8] (Fig. 8) a maximum of 50% of the COD can be transformed into methane, a value which can be confirmed by own investigations. 35 % of the original COD consist after anaerobic digestion of undissolved solids. The remainder consists of bacteria mass and dissolved solids.

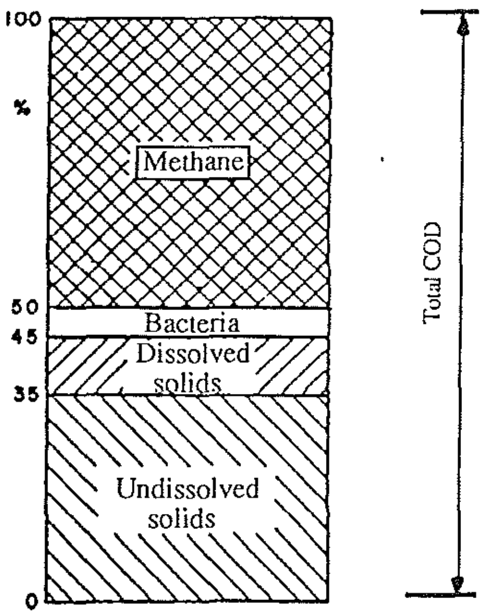


Fig. 8: Conversion of the initial COD in the input volume by the anaerobic degra dation process of a biogas plant into methane, dissolved and undissolved organic solids and bacteria mass according to VAN VELSEN [8]; substrate: liquid pig manure.

- Slaughterhouse waste

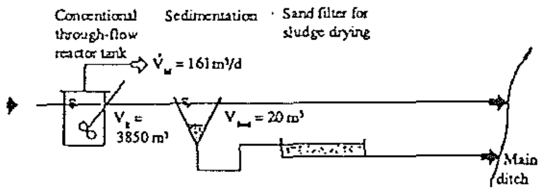
The characteristics and quantities of slaughterhouse wastewater depend greatly on the type of organisation in the slaughterhouse itself. According to each type of production process there are a variety of points where wastewater occurs [9] (Fig. 9).

4.3 The solution

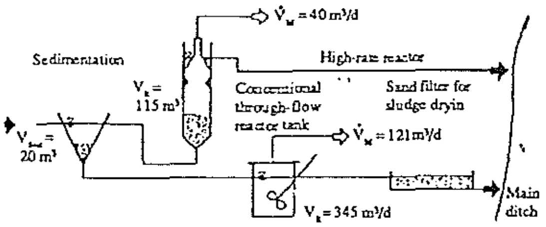
In order to solve these problems a new concept for the treatment of this kind of wastewater was developed [2-6,10].

There are two possible alternatives (Fig. 10):

TROUGH-FLOW PLANT



Alternative A



Alternative B

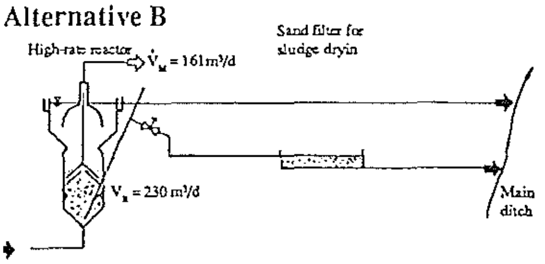


Fig. 10: Selected alternative processes to the anaerobic treatment of wastewater from slaughterhouses and intensive animal farming

4.3.1 Alternative A

Alternative A, a modular double biogas system (MDB-system), is one solution to the wastewater problem. According to this alternative the wastewater is first fed into a settling tank. This is where it initially loses a large part of its coarse, suspended solid matter as sludge. This sludge which has a total solid content of more than five percent can then be treated anaerobically without the danger of processing problems in any of the a. m. construction types of the through-flow plant.

However, this is only a part solution for the whole problem. Depending on the composition of the wastewater only about 50 to 80 % of the anaerobically digestible pollution load can be separated as sludge and transformed into biogas. The remainder is in the effluent from the sedimentation tank. As most of these are dissolved organic compounds this effluent can be treated further in one of the high-rate systems mentioned above.

The cleaning of this wastewater has been evaluated within the GTZ-activities up to now only in the case of one plant [7,12], which treats the effluent from an intensive pig fattening combined with slaughterhouse wastewater. Several other pilot plants, which have been set up at various locations, and from which further data can be obtained are still under construction [6].

4.3.2. Alternative B

The second alternative is the direct treatment of the raw wastewater in a high-rate reactor which has been developed during many years of research and development work [6] and which is now three years under operation. The plant looks like the plant inlustrated in fig. 7b, but contains a special integrated gas-sludge separator for better process control (Fig. 10). The main data about the efficiency of this plant have been published [6, 11].

Presumably, this reactor is also suitable for treatingthedissolvewastewatermentionedabove under alternative A which flows out of the settling tank.

4.4 Operation results

The evaluation of both solutions shows, that

- in each of the above alternatives it is possible to eliminate more than 80% of the anaerobically digestible COD_a and, depending on the substrate,
- more than half of the total COD, and to convert this into the high-grade energy, biogas at a much lower retention time than in a through-flow plant.

4.5 Calculation Examples

This state of the art allows new treatment possibilities, which advantages to make them more clear are to be illustrated in the case of both alternatives by means of calculation example and compared to a classic through-flow solution followed by a sedimentation tank and a sand filter for drying the sludge (Fig. 10).

The slaughtering of a livestock unit incurs about 2 to 4 m³ of wastewater. The COD concentrations tend to be between 3,000 and 17,000 mg/l.

As in the case of liquid pig manure the wastewater contains a high proportion of volatile solids present in suspended form. These solids are only partly anaerobically degradable.

will initially result, after a certain period, in bridging across between the walls of the support materials and lead in horizontal direction to complete blockage of the cross section of the reactor.

When treating the wastewaters in an anaerobic activated sludge or sludge bed process two problems will occur:

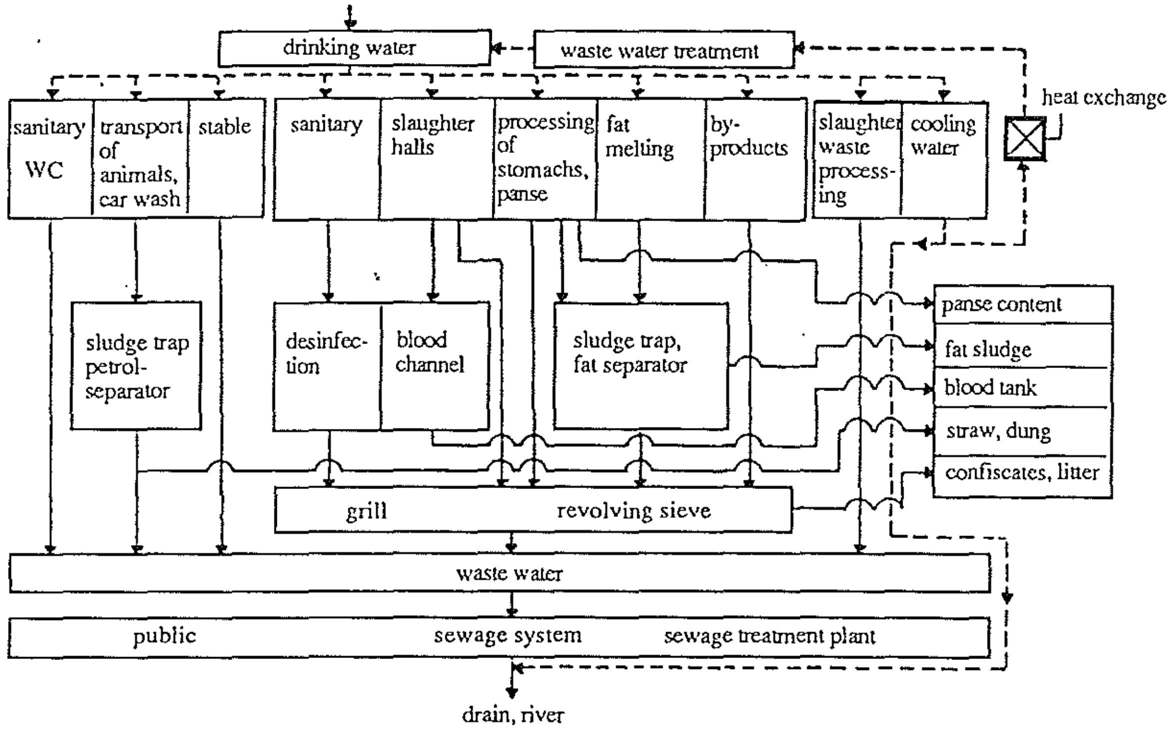


Fig. 9: Process steps and points of wastewater production in slaughterhouses according to STEINER [10]

4.2 The problem

Anaerobic high-rate processes have previously only been used for wastewaters which organic content was present mainly in a dissolved form or at least in a form which could be easily hydrolyzed.

Wastewater from slaughterhouses and from intensive animal farming however contains a high proportion of volatile solids in a suspended form which is only partly digestible.

In applying the results in process engineering, obtained for treatment of the first kind of substrate to wastewater with a high content of coarse suspended solids, problems arise which are not inconsiderable:

If these wastewaters are given into fixed bed reactors without any prior treatment the inert solids proportion under anaerobic conditions

The proportion of inert solid matter which can sediment concentrates in the sludge and significantly reduces the proportion of biologically active biomass in the digester.In this way the efficiency of these reactors decreases. A further negative factor is that particularly the non-dissolved solid matter tends to reduce its specific weight by creating gas which is partly enclosed by the solid matter or is attached to its surface.

The non-dissolved solids normally sink to the bottom - as determined during own tests - at a velocity of 3 -4 m/h. Should gas bubbles attach them they rise at up to 300 m/h to the surface.

This disturbs the settling of the sludge and a relatively high volume of fresh sludge is washed out of the system resulting in an unsatisfactory concentration of biomass in the reactor. Thus the efficiency of the reactor decreases. Additionally there are scum problems which have a negative influence on operation.

For these reasons the direct treatment of this kind of wastewater by one of the a.m. anaerobic high-rate reactors cannot be recommended.

It is not intended to include in this essay all calculations but is restricted to significant features. It must also be pointed out that a number of the values can not be seen as absolutely precise as they are only based upon the first results of the pilot and demonstration plants in Colombia and Thailand [6,7,11,12].

The object of consideration is an intensive animal farming plant with a total stock of approx 2,000 animals corresponding to about 260 livestock units. The amount of wastewater and load of pollution emitted by this farm corresponds approximately to those of a slaughterhouse with an average slaughtering rate of about 20 livestock units per day.

According to Table 2 a flow volume of 77 m³/d as a daily input is derived which has an concentration of anaerobically degradable *CODa* of about 5.97 kg/m³. Thus the COD_a-mass flow volumes to 460 kg/d from which 161 m³ of methane can be obtained daily (Fig. 10 and 11).

- Through-flow plant

The optimum retention time of a through-flow plant amounts to t_R = 25 days if the plant is operated at 30° C. Assuming tropical ambient temperatures lying around 20°C then the retention time is to be extended by the factor $a_{\vartheta R} = 2$ according to Figure 5 on account of the considerrably lower reaction rate compared to 30°C. According to equation (5) the digester volume of the reactor is then to be calculated according to (3) as follows:

$$V_R = t_{R,30} * a_{\vartheta R} * \dot{V}_S \qquad (5)$$
$$= 25 * 2 * 77 = 3,850\ m^3$$

Thus a digester volume of 3,850 m³ is necessary.

If the COD is to be reduced further after anaerobic digestion a secondary sedimentation tank should be added. The volume necessary is approx. 20 m³.

This solution will provide a methane production of 161 m³/d.

- Treatment-alternative A

If however, the sedimentary tank is not added afterwards, but as proposed in a.m. alternative A prior to the anaerobic treatment one will achieve the volume flows, CSB_a-mass flows and the methane productions as shown in Fig. 11. For the treatment of sludge a through-flow reactor would be suitable. The volume V_ϑ of this reactor for treating sludge is calculated according to equation (5) and the data obtained from the evaluation of this kind of plant [7].

$$V_R = 5 * 2 * 25 = 250\ m^3$$

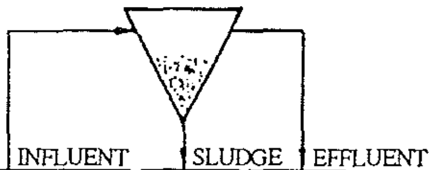
The volume of the high-rate reactor for the anaerobic treatment of the remainder from the sedimentation tank is calculated according to (4) through the volumetric loading rate.

It is:

$$V_R = \dot{V}_S * c_{CODa} / B_{R.CODa} \qquad (6)$$

According to values observed [7] the wastewater should be sufficiently digested by a volumetric loading rate of $B_{R.CODa} = 0{,}6\ kg/m^3{\cdot}d$. This gives a digester volume V_R of $115 / 0{,}6 = 192\ m^3$ at an average retention time t_R of 64 hours.

Fig. 11 summarises the results.



		Influent	Sludge	Effluent
$\dot{V}_S$	m³/d	77	5	72
$\dot{m}_{CODa}$	kg/d	480	345	115
$\dot{V}_M$	m³/d	161	121	40

V_R	m³	250	192
V_{SED}	m³	20	

Fig. 11: Volume flows, COD_a mass flows and daily methane productions in alternative A before and after the sedimentation tank

- Treatment-alternative B

The basis for alternative B is that the type of reactor selected can be operated at a volumetric loading rate $B_{R.CODa}$ of 3 kg/m³.d.

Thus according to equation (6) the following volume is obtained:

$$V_R = 460 / 3 = 153\ m^3.$$

4.6 Summary, Conclusions

The above observations are summarised in Table 3:

Table 3 Comparison of volumes for the reactor and other tanks and the daily methane production of three different anaerobic treatment alternatives

Method	Volume Settling tank m^3	Reactors m^3	Daily methane production m^3/d
Through-flow plant	20	3.850	161
Alternative A	20	250	121
		192	40
total	20	442	161
Alternative B	0	153	161

This table clearly shows that by applying alternative methods the digester volume can be considerably reduced in comparison to a through-flow plants by obtaining an identical amount of methane. This is true especially if the substrate is very diluted.

But even if the substrate has a relative high concentration of pollution as supposed in the above calculated case, a reduction in total construction volume of a factor varying from 8 to 25 is possible.

This means high cost savings in construction, though the benefit of all discussed treatment alternatives, respectivly energy production and reduction of contamination, is the same.

This result clearly shows the direction which is to be taken for further work in the planning and constructing plants for anaerobic treatment of substrates with a high portion of coarse suspended solids.

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SUMMARY

High-rate plants for the anaerobic treatment of wastewater and the production of biogas.

In a comparison of conventional trough-flow plants with more recent models the limits of trough-flow plants become apparent.
It is proved that USAB (upflow anaerobis sludge bed) plants are the more economical alternative for treating highly diluted wastewater since not the retention time, but the volumetric loading is the decisive factor in the production of biogas. The upflow principle is described using practical examples existing in Thailand and Columbia.

SOMMAIRE

Procédés de haute performance pour l'assainissement anaérobe des eaux usées et l'obtention de biogaz.

Les installations à écoulement traditionelles sont comparées à des installations à écoulement récentes et, en même temps, les limites des installations à écoulement sont mises en évidence. Il est démontré que dans le cas d'eaux usées très.fluides les installations à courant ascendant (UASB) représentent l'alternative la plus rentable, car ce n'est pas la période de putréfaction, mais l'espace sollicité qui est décisif. Le principe des installations à courant descendant dans la pratique est illustré d'après des exemples situés en Thaïlande et en Colombie.

RESUMEN

Rendimiento elevado del procediemto para la limpieza anaerobica de aguas residuales y para la extracción de Biogas.

Instalaciones de filtración convensionales se comparan con instalaciones de filtración más modernas y se señalizan los limites de las instalaciones de filtración. Se comprueba que en instalaciones electricas (USAB) de aguas residuales finas presentan la alternativa más económica, porque no el tiempo de pudrición sinó que la capasidad para la producción de Gas es decisivo. En ejemplos de Tailandia y Colombia se explicará el principio electrico